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Dynamic Structures & Materials, LLC

Piezoelectric Step And Repeat Hydraulic Motor Phase I STTR

UCLA

OBJECTIVE:

Development of a compact, high-power, piezoelectric-driven linear motor/actuator to couple with a valveless hydraulic displacement amplifier

PROGRAM SPECIFICS:

- **Phase I funded through the DARPA STTR Program at $99k, Contract No DAAH01-99-C-R209**
- **Dynamic Structures and Materials is prime contractor with UCLA as STTR University partner**
- **Phase I effort period of performance: July, 1999 through May, 2000**
- **Phase II proposal currently under consideration**

APPLICATIONS:

Current military/industrial partners need large stroke actuator for missile fin control, hydraulic servo control, precision optical machining and semi-conductor machining. DSM is working with industrial partners and have obtained matching funds for Phase I ($16k + $50k). Phase II matching funds ($520k) are currently under consideration.

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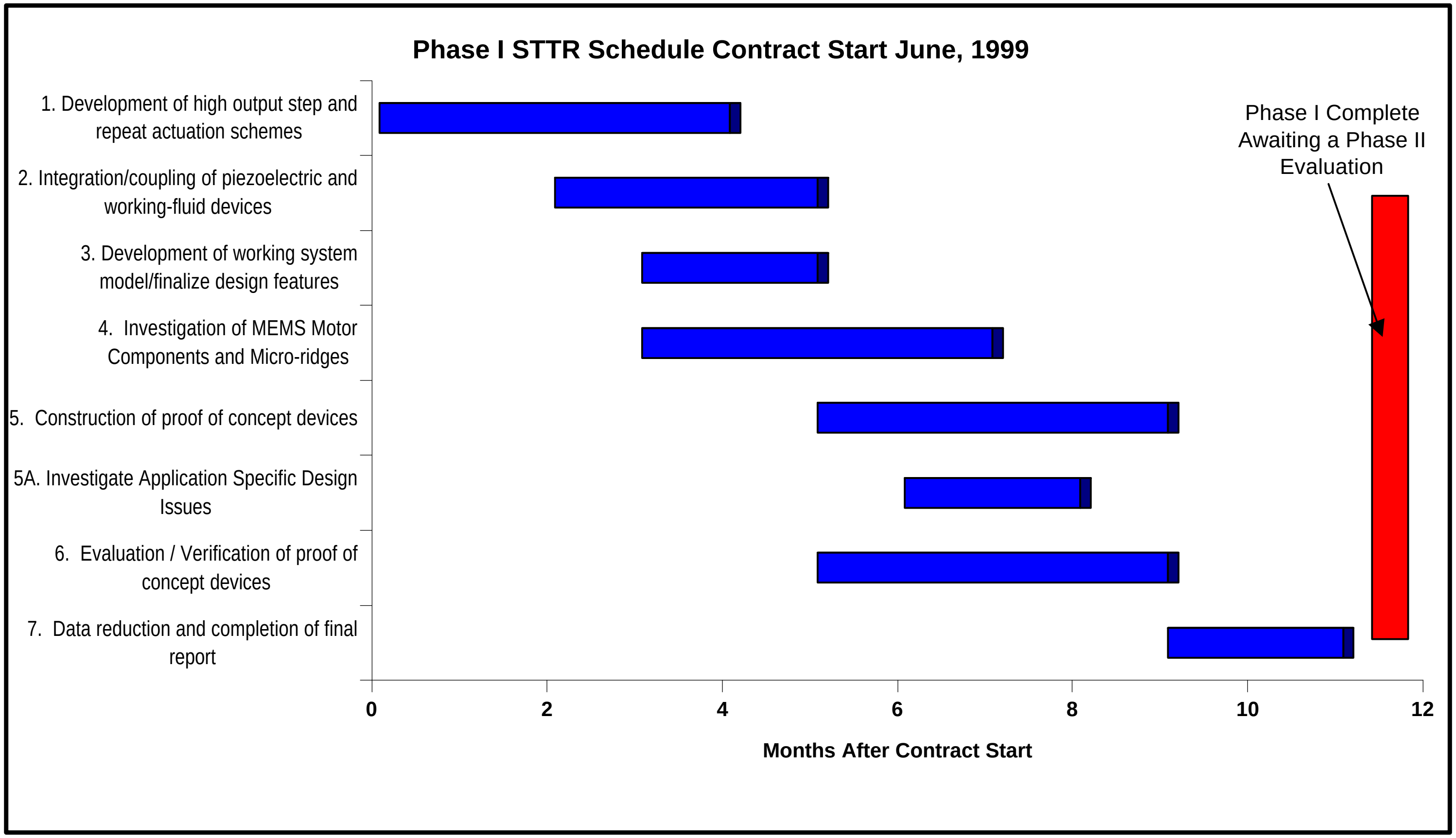
Project Schedule



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Contractor and Subcontractors

Small Business Prime Contractor:

- Dynamic Structures and Materials - PI: Jeff Paine
- Contracted for 65% of the Phase I effort.
- Responsible for:
  - Motor Design Work
  - Fabrication and Testing.
  - Commercialization and
  - Application Testbed

University Research Partner - Subcontract:

- UCLA - Active Materials Lab - PM: Greg Carman
- Contracted for 35% of the Phase I effort.
- Responsible for:
  - MEMS Components Fabrication and Testing
  - PZT characterization and
  - PZT Testing

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Program Accomplishments

UCLA

- Identified design Issues behind PZT motor Performance
  - Fabricated, tested and evaluated multiple motor configurations
  - Design, construction and testing of inchworm motor using microteeth
- Fabricated final Phase I prototype with following performance levels
  - Stroke: 25 mm
  - Speed: 20 mm/s (operating at 500 Hz)
  - Force: 50 lb
  - Weight: 1 kg
- Designed Electronics Package with Motor Driver and Controller
  - 130 W average power was required to drive 3 channels (PZT= 32 μF) at 500 Hz
  - Three Channel Driver fits into a 10” x 14” x 3” volume
- Identification of Missile Guidance Application and Prototype Agreement
- Thorough characterization of g-tolerance of piezoelectric stacks

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Gained by/ Learned

Identified fundamental design Issues behind PZT motor Performance

Developed some new motor designs that are being investigated by Tennessee
- Tech Grad Students as Part of Grad Program

New PZT Motor Concept was developed and tested
- Patents filed for new concept.

Identified control methods for efficiently driving PZT motors with a National Instruments micro-controller interface
- Microridge based designs
- Inchworm Type Motor Designs
- New Motor Concept

Developed more compact power electronics package

Identified new customers for compact motors
- Kicked off DSM's Motor Line

Identified Strength levels for MEMS Micro-ridges

Identified G-hardness level for a number of PZT stack materials

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Motivation for PZT Motor Actuators

Table 1. Comparison of Energy and Power Output for Actuator and Linear Motor Technologies

Material or Technology	Safe or Useable Levels or Ranges when used in Actuator Devices							
	Dimensions	Force	Stroke	Energy /Vol.	Energy /Mass	Freq.	Power /Vol	Power /Mass
	mm	N	mm	J/m^3	J/kg	Hz	W/m^3	W/kg
Raw PZT Stacks	(11 x 11) x 100	1210	0.110	11 k	1.45	1000	11 M	1450
Raw SMA Wire	(2 ∅) x 100	1300	2.0	8.3 M	1333	5	41.5 M	6667
Piezo Actuator	(19 x 25) x 125	1210	0.110	2.2 k	0.59	1000	2.2 M	594
SMA Actuator	(3 x 10) x 110	1300	2.0	790 k	160	5	4 M	810
Magnetostrictive Actuator	(32 ∅) x 81	110	0.05	84	0.013	3000	0.26 M	40
Voice Coil	(45 ∅) x 29	13.8	6.1	1.8 k	0.36	800	1.4 M	280
PZT Linear Step Motor	(45 x 28) x 150	120	25	15.9 k	3.0	NA	10.2 k	1.92
Kollmorgan Linear Motor	(75 x 33) x 129	40	25	3.1 k	0.69	NA	31 k	6.9

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Phase I Motor Performance

- Motor uses simple action to produce high driving force. One Phase I prototype achieved nearly 170 lb pushing forces.
- Weight is 1 kg but can be reduced to 0.5 kg for current performance levels by optimizing the structural mass and simplifying design.
- Size is 45 x 28 mm by 150 mm long. Phase II design can be reduced to 30 x 25 mm by 120 mm long while still maintaining same energy output.
- Phase I Stroke is set at 1 inch (25 mm) but can be turned into a continuous drive motor.
- Simple design allows high operating frequency. Phase I motor was limited to 500 Hz level because of simple prototype limitations. Phase II prototype will operate at 2kHz or higher.
- Motor is constructed using simple construction techniques. Exotic or complex fabrication techniques are avoided.
- Phase I speed was +20 mm/s. Phase II speeds are set to be 100 mm/s while maintaining force output in excess of 100 lb.

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Prototype Driver Electronics

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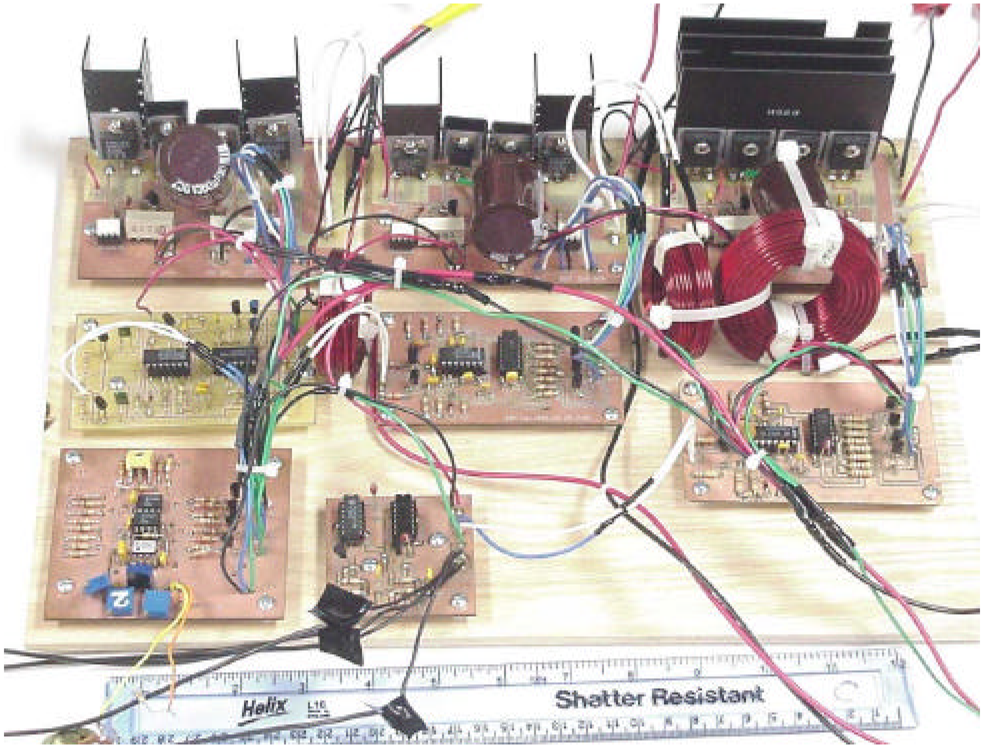
Driver Concept

A pulse-driven LC circuit moves the PZT voltage smoothly to the desired level. A softly turned-on switch maintains the PZT voltage. Most of the inductor energy is efficiently returned to the power supply.

Performance Highlights

- **Only 130 W average power required to drive a 32 μF load at 500 Hz**
- **1st Gen. Prototype (right) has 3 channels in space of 10” x 14” x 3”.**
- **Phase II prototype can easily be reduced once the load and driver are optimized.**



1st Generation PZT Motor Driver

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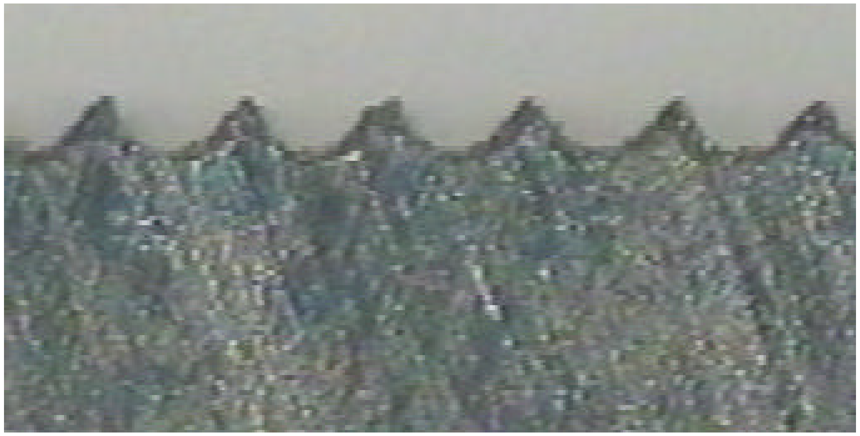
Titanium Micro-Ridge Experiments

DSM implemented an early step-motor design (right) using titanium microteeth (left) with pitches of 0.006” and 0.008”.

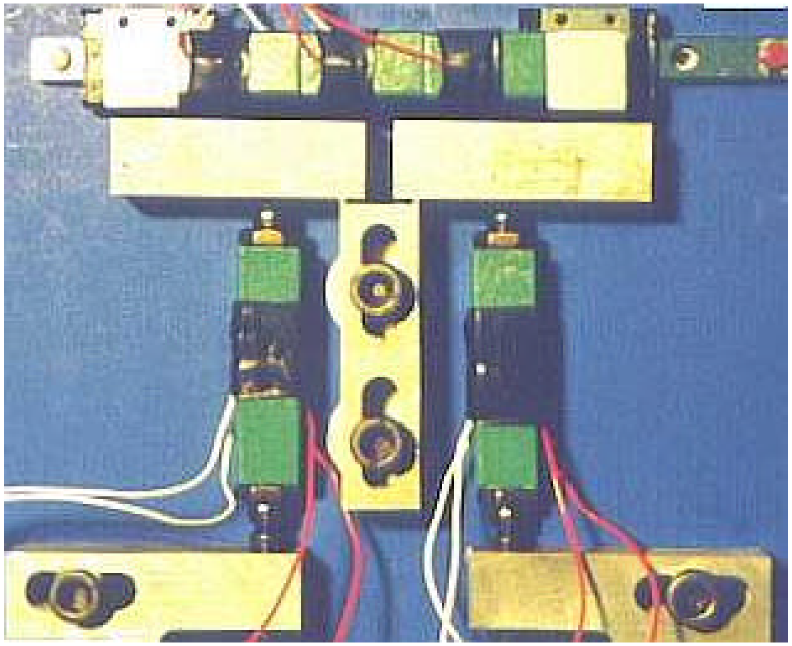
Titanium teeth have excellent static force carrying capabilities.

Very low holding forces were observed due to misalignment of the interacting teeth.

Load variation and vibration shifted step size leading to poor alignment and tooth engagement.



Wire EDM cut 0.008” pitch teeth in titanium



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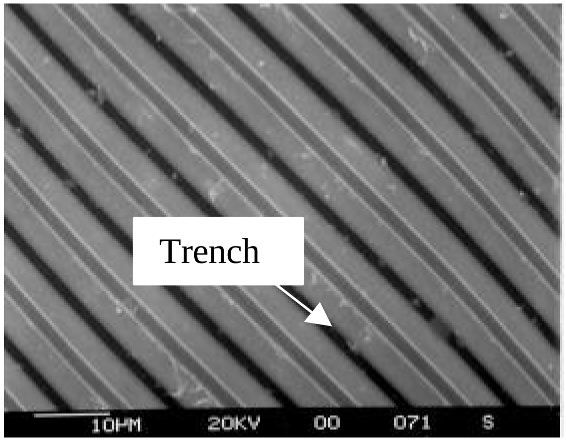
Silicon Micro-Ridges

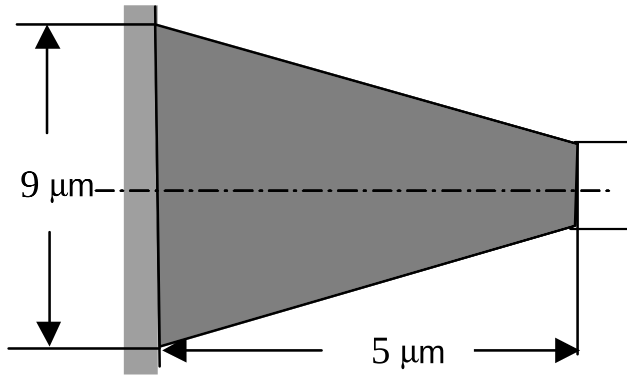
UCLA produced Micro-Ridges in Silicon with the Dimensions below.

The micro-ridges demonstrated excellent holding power

After DSM's lack of success with the Titanium teeth, the micro-ridge design was put on hold.



Top view of trapezoid shape microridges



Sketch of cross section of the ridge

SEM photo of the trapezoidal shaped micro teeth in Silicon.

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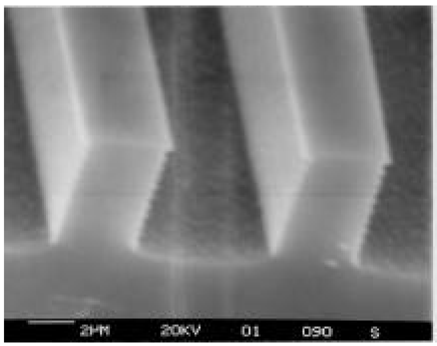
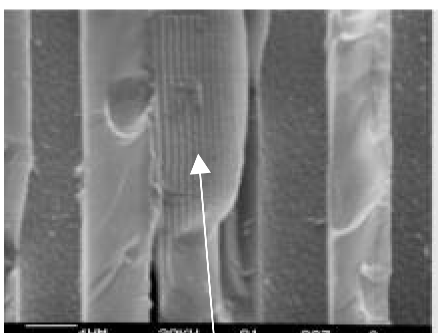
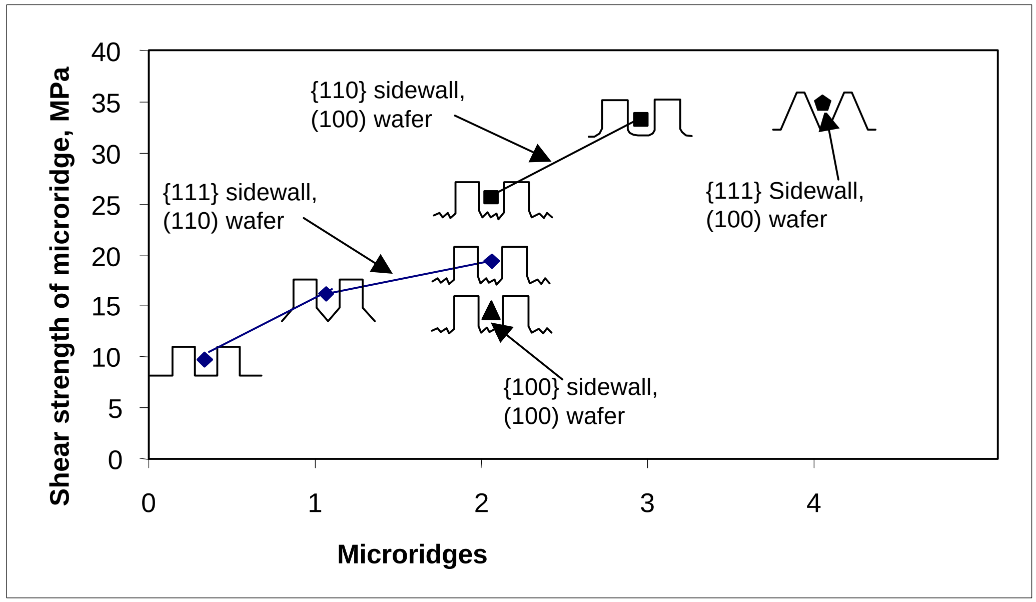
Summary of Micro-Ridge Strength



Deep RIE



Pure Shear Fracture



1. Strengths are both orientation and shape related
2. Trapezoid and round bottom shape the best

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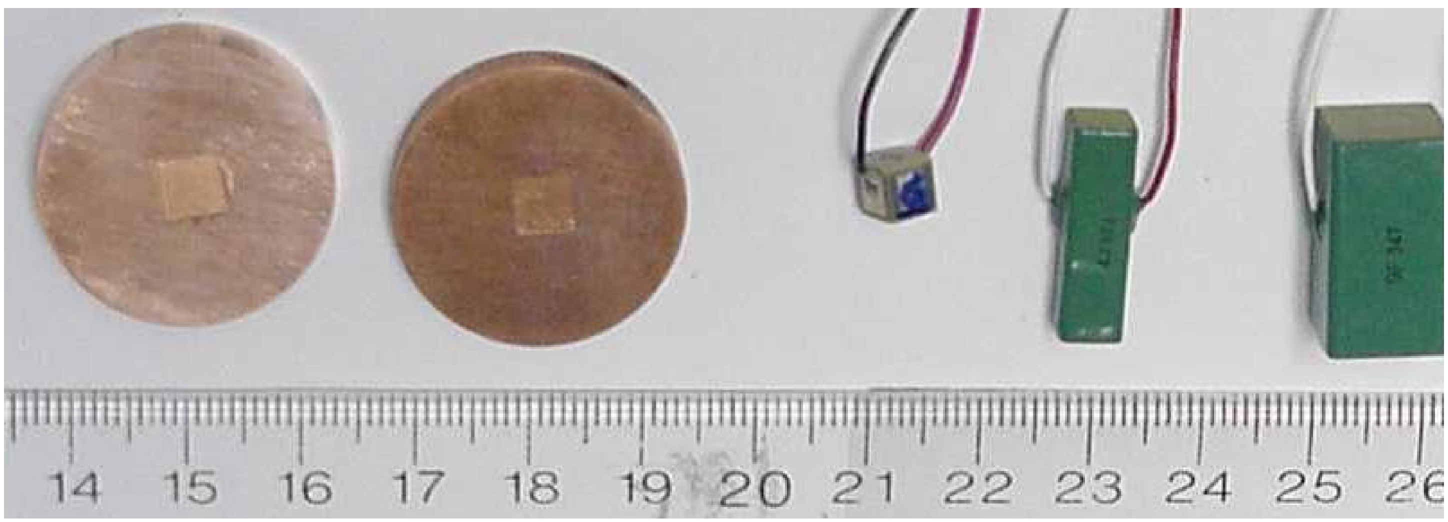
PZT G-hardening Study

One military customer needed to know if the new motor design could withstand a 30 kG loading condition.

DSM and UCLA characterized the static compressive strength of various PZT stack materials as a first step in determining PZT materials g-hardening capabilities.



PZT stack samples similar to the ones tested in compression. A 10 x 10 x 20 stack, a 5 x 5 x 20 stack, a 5 x 5 x 5 stack, and copper pressure plates (right to left)

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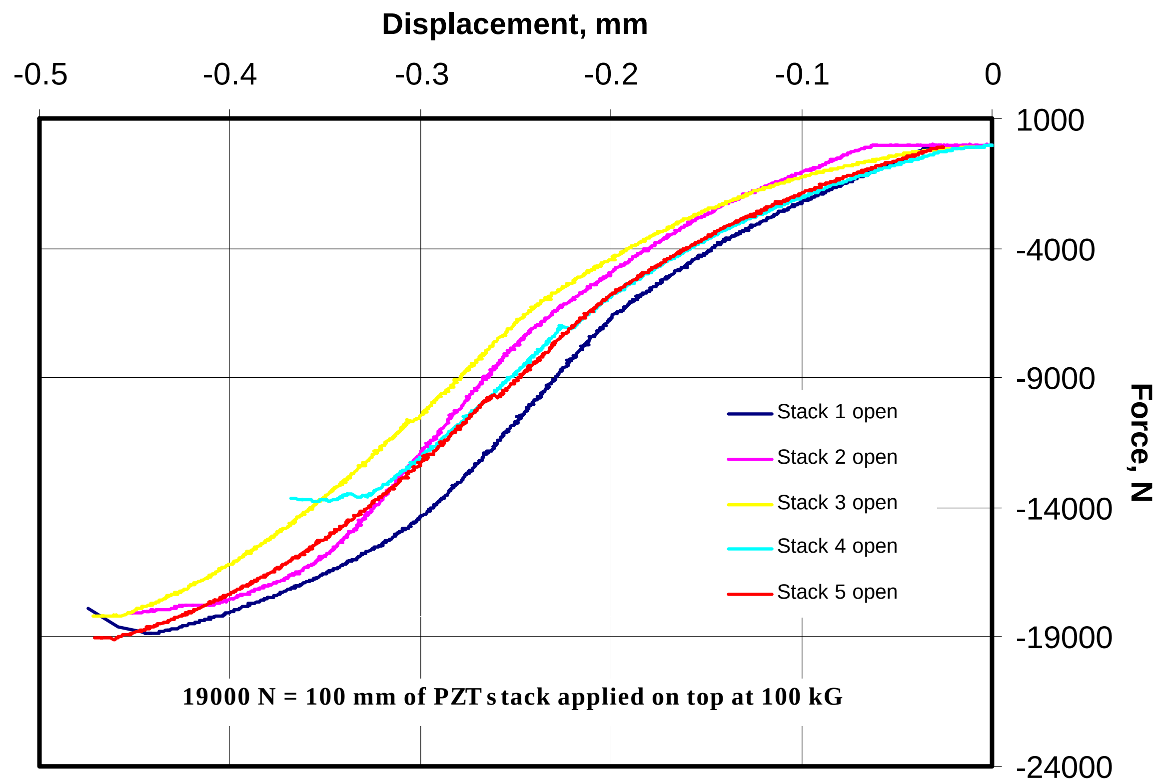
PZT G-hardening Study

5 x 5 x 5 mm PZT Stacks under compression load demonstrate a static strength level suggesting that they can withstand nearly 100 kG. PZT expansion performance after 30 kG was confirmed.



PZT Stacks Crushed in Open Circuit Operation

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